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The Complex and Spatially Diverse Patterns of Hydrological Droughts Across Europe

D. Peña-Angulo[1], S. M. Vicente-Serrano[1], F. Domínguez-Castro[2,3], J. Lorenzo-Lacruz[4], C. Murphy[5], J. Hannaford[6], R. P. Allan[7], Y. Tramblay[8], F. Reig-Gracia[1], and A. El Kenawy[9]

[1]Pyrenean Institute of Ecology, Spanish National Research Council (CSIC), Zaragoza, Spain, [2]Aragonese Agency for Research and Development Researcher (ARAID), Zaragoza, Spain, [3]Department of Geography, University of Zaragoza, Zaragoza, Spain, [4]Department of Human Sciences, University of La Rioja, La Rioja, Spain, [5]Department of Geography, Irish Climate Analysis and Research UnitS, Maynooth University, Maynooth, Ireland, [6]Centre for Ecology and Hydrology, Wallingford, UK, [7]Department of Meteorology and National Centre for Earth Observation, University of Reading, Reading, UK, [8]HydroSciences Montpellier Center, Montpellier, France, [9]Department of Geography, Mansoura University, Mansoura, Egypt

Key Points:

- The hydrological drought trend shows a decrease over Northern Europe and an increase over the central and South of Europe for 1962–2017
- The monthly streamflow trend (Europe) shows a decrease in all months (South) and warm months (North), and an increase in cold months (North)
- The Monthly Streamflow of Europe Dataset (MSED) and map viewer is freely available (http://msed.csic.es/)

Correspondence to:
D. Peña-Angulo,
dhaispa@gmail.com

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Author Contributions:
Conceptualization: D. Peña-Angulo, S. M. Vicente-Serrano
Data curation: F. Reig-Gracia
Formal analysis: D. Peña-Angulo, F. Domínguez-Castro, J. Lorenzo-Lacruz, C. Murphy, J. Hannaford, R. P. Allan, Y. Tramblay, A. El Kenawy
Investigation: D. Peña-Angulo, Y. Tramblay
Methodology: D. Peña-Angulo, S. M. Vicente-Serrano
Software: F. Reig-Gracia
Supervision: S. M. Vicente-Serrano
Validation: F. Domínguez-Castro, J. Lorenzo-Lacruz, C. Murphy, J. Hannaford, R. P. Allan, Y. Tramblay, F. Reig-Gracia, A. El Kenawy
Visualization: F. Domínguez-Castro, J. Lorenzo-Lacruz, C. Murphy, J.

Abstract This study presents a new data set of gauged streamflow (N = 3,224) for Europe spanning the period 1962–2017. The Monthly Streamflow of Europe Dataset (MSED) is freely available at http://msed.csic.es/. Based on this data set, changes in the characteristics of hydrological drought (i.e., frequency, duration, and severity) were assessed for different regions of Europe. Due to the density of the database, it is possible to delimit spatial patterns in hydrological droughts trend with the greatest detail available to date. Results reveal bidirectional changes in monthly streamflow, with negative changes predominating over central and southern Europe, while positive trends dominate over northern Europe. Temporally, two dominant patterns were noted. The first pattern corresponds to a consistent downward trend in all months, evident for southern Europe. A second pattern was noted over central and northern Europe and western France, with a predominant negative trend during warm months and a positive trend in cold months. For hydrological drought events, results suggest a positive trend toward more frequent and severe droughts in southern and central Europe and conversely a negative trend over northern Europe. This study emphasizes that hydrological droughts show complex spatial patterns across Europe over the past six decades, implying that hydrological drought behavior in Europe has a regional character. Accordingly it is challenging to adopt "efficient" strategies and policies to monitor and mitigate drought impacts at the continental level.

1. Introduction

Drought is one of the most damaging and recurring natural hazards, with devastating socioeconomic, ecological and even political impacts (Ide, 2018; Von Uexkull et al., 2016; Wilhite and Pulwarty, 2017). Characterizing the severity and risk of drought is not an easy task, given that drought events are rarely confined to a single location; instead, they can affect large areas and extend over months, years, or even decades (Van Loon, 2015). Moreover, drought evolution is influenced by a variety of hydrometeorological variables (e.g., precipitation, evapotranspiration, runoff), which imposes further complexity on drought assessment (Mishra & Singh, 2010; Sheffield et al., 2012). In this context, there are different types of drought: meteorological, hydrological, agricultural, and socioeconomic (Cayan et al., 2010; Mishra & Singh, 2010; Wilhite, 2000). Among them, hydrological droughts are of particular concern for policy makers, due to the reliance of society and ecosystems on water availability in rivers and aquifers (Parry et al., 2005; Rivera et al., 2021; Van Loon, 2015).

Hydrological drought is associated primarily with lack of water in hydrological systems, as evidenced by abnormally low streamflow, or deficits in levels of lakes, reservoirs or groundwater (Tallaksen & Van Lanen, 2004). Other sectors may be impacted by these abnormal hydrological conditions, including the quality of aquatic and riparian habitats, water quality, water supply for domestic, agricultural and industrial uses, riverine transport and hydropower production, among others (Parry et al., 2012). Due to recent climate change and variability, as well as unprecedented rates of urbanization, industrialization, and population growth, these negative impacts have accelerated in recent decades (Dai, 2021).

Hannaford, R. P. Allan, Y. Tramblay, F. Reig-Gracia, A. El Kenawy
Writing – original draft: D. Peña-Angulo
Writing – review & editing: D. Peña-Angulo, S. M. Vicente-Serrano, F. Domínguez-Castro, J. Lorenzo-Lacruz, C. Murphy, J. Hannaford, R. P. Allan, Y. Tramblay, A. El Kenawy

Although drought is driven mainly by lack of rainfall, other factors (e.g., atmospheric evaporative demand, storage in ice and snow, land use change) can also play a role in the occurrence of hydrological drought (Avanzi et al., 2019; Van Loon & Laaha, 2015). Numerous studies indicate that the projected decrease in precipitation across many regions worldwide, particularly in the subtropics, accompanied by a more general increase in atmospheric evaporative demand and thus evapotranspiration, will likely accelerate the severity of hydrological drought in the coming decades on a global scale (Dai, 2021; Diffenbaugh et al., 2015; Prudhomme et al., 2014). Furthermore, anthropogenic climate change will intensify the hydrological cycle including its seasonal and year to year variability (Allan et al., 2020) and influence atmospheric/oceanic circulation (Bardossy & Caspary, 1990; Hurrell & Van Loon, 1997), likely inducing significant changes in streamflow regimes and climate extremes like drought (Dai, 2021; IPCC, 2013; Spinoni et al., 2014), even in those regions which on average will become wetter in a warming world.

In Europe, there is increasing interest in studies examining long-term changes in hydrological droughts in order to detect any emerging trend that could be linked to climate change processes (Hannaford, 2015). Earlier studies mostly focused on hydrological drought trends on a regional scale (e.g., Harrigan et al., 2018; Lorenzo-Lacruz et al., 2012; Myronidis et al., 2018; Wilson et al., 2010; Wu et al., 2018). Unfortunately, the few investigations conducted on hydrological drought trends at a continental scale have employed only a sparse network of gauges (e.g., Fleig et al., 2006; Hisdal et al., 2001; Van Lanen et al., 2013). Exceptionally, Hisdal et al. (2001) characterized hydrological droughts by analyzing trends for 612 gauging stations in Europe spanning different periods between 1962 and 1995. They found that it is difficult to conclude that drought conditions have become more severe or frequent in Europe. Later, Stahl et al. (2010) assessed streamflow trends (but not explicitly drought indicators) from 1962 to 2004 using 441 gauging stations across 15 European countries—This data set is selective by design, to focus on "near natural" catchments that are free of major human impacts on low flow regimes. In terms of streamflow trends across Europe, Stahl et al. (2010) found two dominant spatial patterns: increasing streamflow (and low flows) in western and northern Europe and the opposite pattern in southern and central Europe. Based on a network of 1874 gauges from Ireland, the United Kingdom, France, Spain, and Portugal, Vicente-Serrano et al. (2019) found that the physical drivers of streamflow trends (specifically on annual average flows) vary considerably between northern and southwestern Europe—Increases in the north are strongly climate-driven while in the south irrigation and land cover influences play a role as well as climate.

However, while these studies have provided some large-scale context for potential changes in hydrological drought, the transferability of conclusions is limited by the relative sparseness and geographical biases of the datasets, particularly given the predominance of data from northern and western Europe and relative lack of coverage in the east and south. At the same time, strong spatial variability of hydrological droughts in various parts of Europe has been linked to different local/regional characteristics (Barker et al., 2016; Lorenzo-Lacruz et al., 2013). A quick inspection of these studies therefore highlights the need to analyze long-term changes of hydrological droughts from a wide continental perspective. This assessment is useful for better understanding the general patterns and regional divergences of hydrological drought trends and accordingly a proper characterization of the drivers of these changes at various spatial scales across Europe.

In the present study, we employ a newly developed long term (1962–2017) and dense (N = 3,224) network of gauging stations across Europe to investigate whether, in the context of climate change, hydrological droughts show distinct temporal and spatial changes across the continent. Our findings can contribute to more effective planning and management of water resources in Europe and a reliable assessment of the different impacts of drought on society and environment.

2. Materials and Methods

2.1. Data

Monthly streamflow data were obtained from national and international hydrometric, scientific and water management agencies across Europe: Agencia Catalana de l'Aigua (Spain), Centro de estudios y experimentación de obras públicas (Spain), Confederación Hidrográfica del Guadalquivir (Spain), Ministerio para la Transición Ecológica (Spain), Environmental Protection Agency (Ireland), Ministère de l'Ecologie, du Développement durable et de l'Energie (France), Sistema Nacional de Informacao de Recurso Hídricos (Portugal), National River Flow Archive (UK), Global Runoff Data Center (WMO). In addition, data was obtained from the gauging stations

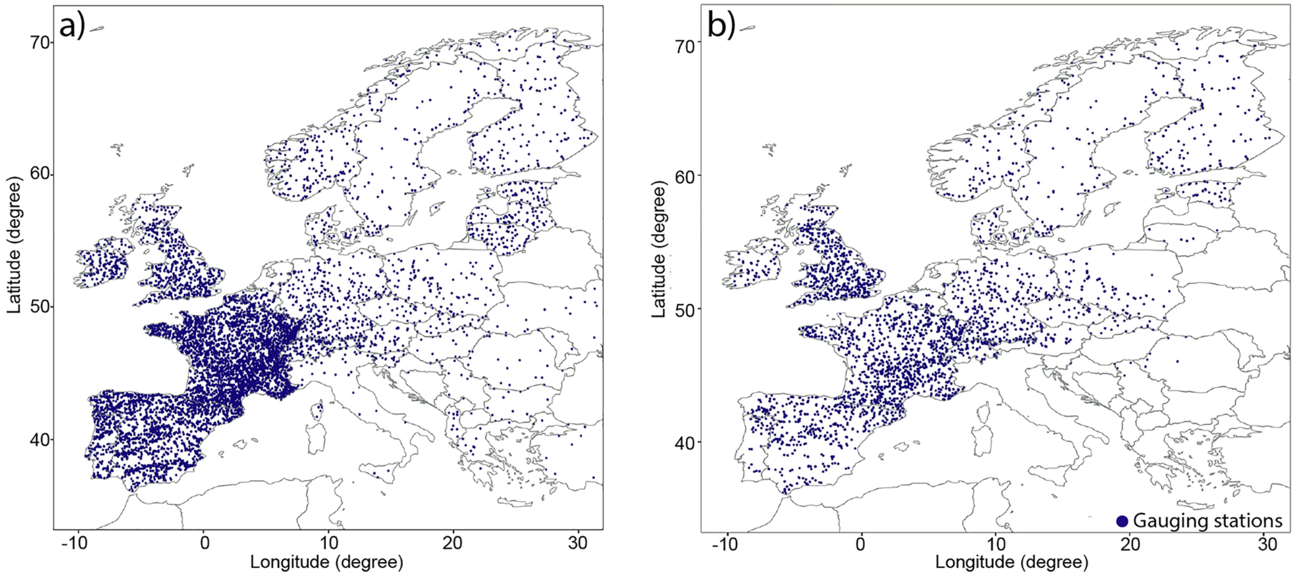

Figure 1. Spatial distribution of the gauging stations in the study area: (a) The full database of stations collected from different sources of information, and (b) the selected stations retained for analysis.

published in the study of Vicente-Serrano et al. (2019). For the period 1962–2017, data from a total of 5,529 stations were available (Figure 1a). Gauging stations are present in catchment with different geographical characteristics, and some are natural, while others are regulated. As gaps were present in many series, reconstruction was undertaken following the methodology described by Vicente-Serrano et al. (2019). Specifically, a reference series was created for each target (candidate) station using data from nearby stations located no more than 100 km away, with a common period of at least 7 years, and a Pearson's r correlation greater than 0.7. Series with at least 75% of data available for the years 1962–2017 were retained.

As observed by Vicente-Serrano et al. (2019), the first decade of the study period is associated with the highest proportion of reconstructed data. Accuracy statistics for the reconstruction process were evaluated using the Percentage Bias and Pearson's r derived from the comparison between observed and reference series. In general, the comparison of observed and predicted monthly streamflow datasets yielded positive results, with more than 90% of reconstructions returning a Pearson's $r > 0.70$). For the years 1962–2017, a total of 3,324 stations were included in the final data set, evenly distributed throughout Europe (Figure 1b).

2.2. Methods

2.2.1. Hydrological Drought Quantification

A hydrological drought is defined as a time period with streamflow below a predetermined threshold that can be related to water deficits (Fleig et al., 2006). The Standardized Streamflow Index (SSI) was used to identify hydrological drought events (Barker et al., 2016). This index compares hydrological drought in different locations irrespective of flow magnitude or river regime characteristics. The monthly streamflow series was transformed into standardized z-scores (Lorenzo-Lacruz et al., 2013). To obtain a reliable SSI that encompasses large variability in the statistical properties of the monthly data, the series were fitted to the most suitable probability distribution, according to the minimum orthogonal distance between the sample L-moments at site i and the L-moment relationship for a specific distribution, selected from among the general extreme value, the Pearson Type III, the log-logistic, the log-normal, the generalized Pareto and the Weibull distributions. For each streamflow series six SSI series were calculated, corresponding to each of the six probability distribution used, with the selected series showing the most robust adjustment (minimum orthogonal distance in L-moments diagram). After calculating SSI, a threshold of −0.84 was applied to identify the onset of hydrological drought events. This threshold corresponds to the expected event with a return period of 5 years (Lorenzo-Lacruz et al., 2013).

The severity, frequency, and duration of droughts associated with the identified hydrological events were quantified (Van Loon, 2015). Specifically, the frequency is defined as the number of events per year, while the duration of an event refers to the number of months from onset (SSI = −0.84) to termination (SSI = 0). Drought severity was defined as the absolute value of the integral area between the value of the SSI at drought onset and termination in the period comprising the duration of an event (Fleig et al., 2006; Lorenzo-Lacruz et al., 2013; Spinoni et al., 2014).

2.2.2. Spatial Regionalization

In order to identify homogeneous regions in terms of the evolution of hydrological droughts, we used a spatial classification approach. We applied a cluster analysis, with the aim of grouping variables with similar properties based on similarities or differences between feature vectors in a data set (Dikbas et al., 2013). In this study, the K-Means clustering method was applied to define homogeneous groups (clusters) of gauging stations according to their monthly SSI. By minimizing the Euclidean distance between each variable and the nearest cluster center, the K-Means method divides the data set into K clusters (Steinley, 2006). To identify a reasonable number of clusters, we applied a set of performance indicators, including the within-cluster sum of square errors (WSS) metric and post-visualization (El Kenawy et al., 2013; Zhang et al., 2016).

In the cluster analysis of the monthly SSI a significant seasonal variability is present. However, in the hydrological drought trend analysis, we are interested in extracting the general behavior. For this reason, the gauging stations have been grouped into independent clusters of seasonality, and each station has been assigned to the cluster more frequently in most months. Lastly, in each cluster, the gauging station that shows the highest correlation with the rest of the stations was selected as representative to analyze the time series in detail.

2.2.3. Trend Analysis

We analyzed the magnitude of change in the monthly SSI, as well as the annual duration, frequency and severity of drought events, over the period 1962–2017 using the Ordinary Least Squares regression method (Moberg et al., 2006). The statistical significance of these changes was tested using the modified Mann-Kendall test (Hamed & Ramachandra Rao, 1998) which allows for consideration of autocorrelation by returning the corrected probability values after accounting for temporal pseudo-replication (Alexander et al., 2006; Hamed & Ramachandra Rao, 1998; Kiktev et al., 2003). To visualize the findings, positive/negative trends were presented in red/blue colors, while the significance of trends, following the Mann–Kendall test, was grouped into three main categories: Non-significant, significant at $p < 0.05$, and significant at $p < 0.01$. Finally, we obtained the percentage of gauging stations with positive/negative and significant/non-significant trends for each cluster of the monthly SSI and for changes in the characteristics of drought events.

The false discovery rate (FDR) procedure is applied to the Mann-Kendall test results of the monthly SSI to check if the trends are regionally significant (Tramblay et al., 2019). The detected trends are regionally significant if at least one local null hypothesis is rejected according to the regional significance level (Wilks, 2016). For consistency with the local trend analysis, the global significance level is also set to 5% in the FDR procedure. This study shows the percentage of stations that show a significant trend (p-value < 0.05 and p-value adjust< 0.05) for in the SSI month.

3. Results

3.1. Features of the Monthly Streamflow of Europe Dataset (MSED) and Map Viewer

The reconstructed monthly streamflow of 3,224 gauging stations for Europe in the 1962–2017 period are included in the MSED map viewer. The MSED map viewer includes the location and the graphic representation of the temporal serie (hm3/month) of 3,224 gauging stations. All information available in the MSED map viewer can be downloaded in txt format, freely available on the website http://msed.csic.es/, maintained by the Spanish National Research Council (CSIC). The folder download has geographic information (coordinates, altitude, country and source of data) and information on the reconstructed monthly streamflow (hm3) of each station.

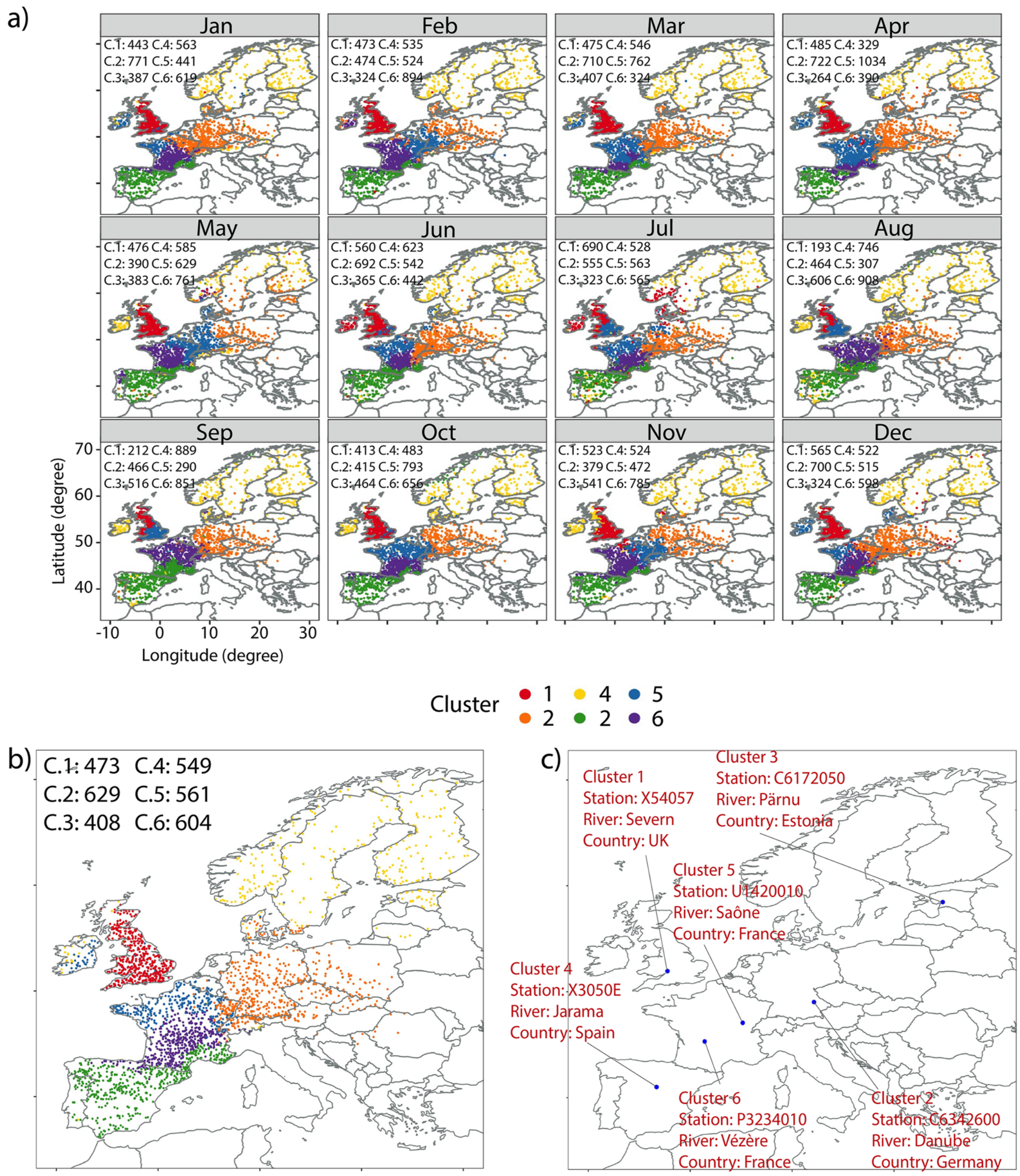

Figure 2. Spatial distribution of (a) the six clusters corresponding to monthly Standardized Streamflow Index (SSI) (the number of gauges in each cluster is also noted), (b) the six generalized clusters summarized from the cluster most frequent in the monthly SSI, and (c) the gauging stations selected as representative of the monthly SSI series in each cluster.

3.2. Spatiotemporal Characteristics of Monthly Streamflow in Europe

Monthly SSI series were clustered into six homogenous regions, with similar temporal evolution from 1962 to 2017 for all months (Figure 2a). The first cluster broadly represents Great Britain across most months, apart from summer months when spatially this cluster is reduced to the north of Britain. The second cluster was assigned mainly to central Europe and is very consistent throughout the year, excluding May. The third cluster is presented in Europe's northernmost region. Norway, Sweden, Finland, Estonia, Latvia, and Lithuania are mostly occupied by this cluster, although Ireland was occasionally included in this cluster in May and from August to November. The fourth cluster is located in the Iberian Peninsula and southeast of France. This cluster is notable for maintaining a high level of spatial consistency over most months. Exceptionally, in April, it only includes the Iberian Peninsula. As compared to other clusters, the fifth and sixth clusters, which are located between the south and central Europe, showed more heterogeneous behavior throughout the months. Specifically, the fifth cluster mostly represents northern and western France, and it occasionally includes Ireland, part of Great Britain, and

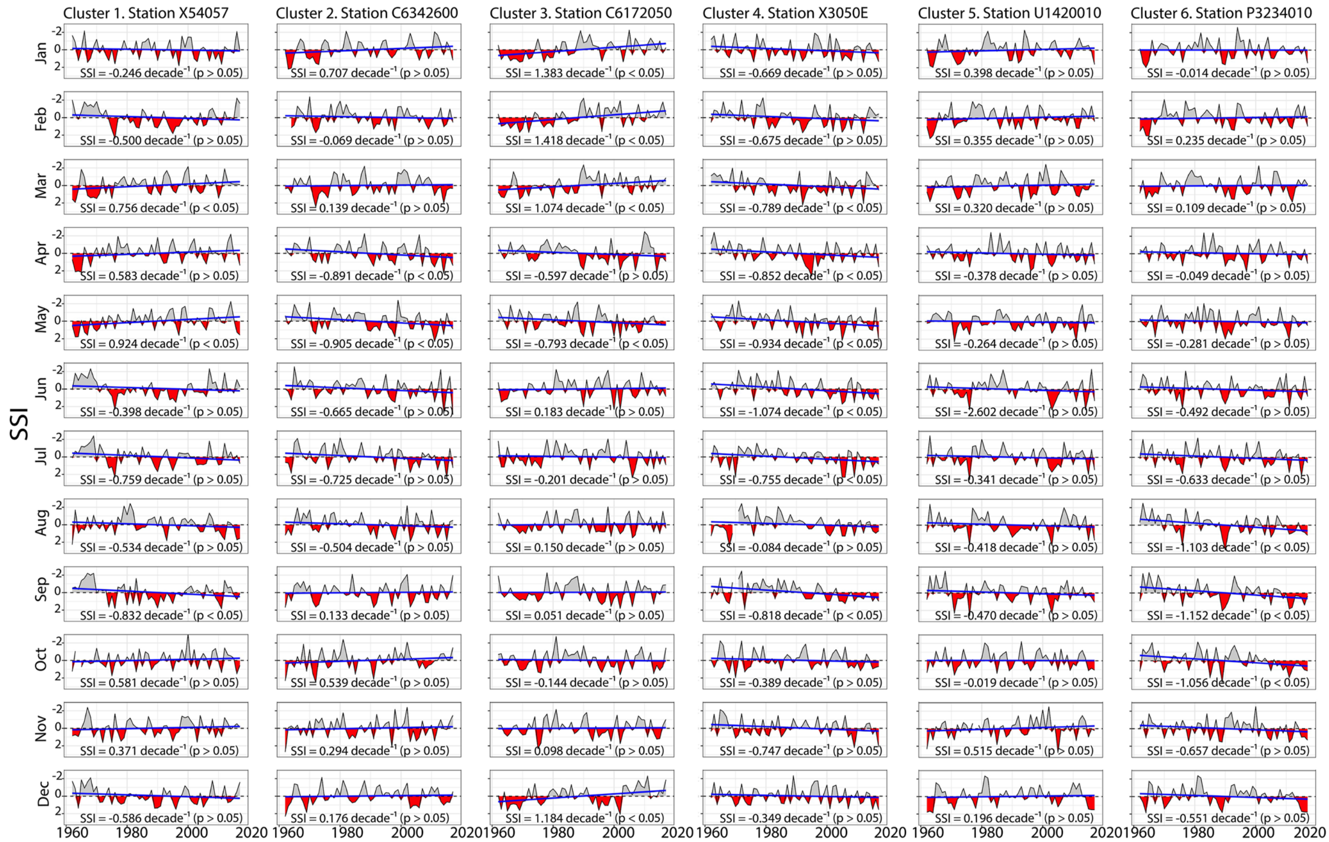

Figure 3. Temporal evolution of the monthly Standardized Streamflow Index (SSI) for each cluster. The magnitude of change, the p-value and positive (gray)/negative (red) SSI values are presented for each panel.

southern Germany. On the other hand, the sixth cluster represents the south of France; its spatial extent varies from one month to another.

From the cluster analysis of the monthly SSI series, six cluster groups are obtained. These cluster groups are relatively spatially homogeneous, although, some seasonal variations are observed. The general spatial patterns of the cluster analysis were obtained by assigning the most frequent monthly cl uster to each gauging station (Figure 2b). Cluster 1 corresponds to Great Britain, cluster 2 spans a wide region in central Europe, cluster 3 occupies northern Europe and the west of Ireland, cluster 4 corresponds to the Iberian Peninsula and southeast France, cluster 5 spans the north and west of France and the east of Ireland, cluster 6 represents central and southern France.

Subsequently, the gauging station in each cluster that shows the highest correlation with the rest of the stations was selected in order to analyze the time series in detail (Figure 2c). Figure 3 depicts the temporal evolution of monthly SSI for the six representative gauging stations of each clusters. For the first cluster, the X54057 station (Severn River, Great Britain) exhibited a slight negative trend (a decrease in streamflow) from June to February, while a positive trend (an increase in streamflow) was noted during springtime (March, April and May). The second cluster is represented by the C6342600 station, Danube River, Germany. We noted two patterns for this station: A positive trend from September to March, and conversely a negative trend from April to August. For the third cluster, two temporal patterns were observed for the C6172050 station (Pärnu River, Estonia), with a positive trend from December to March, and a negative or lack of trend from April to November. The time series of the X3050 E station (Jarama River, Spain), representative of the fourth cluster, revealed a strong negative trend in SSI in all months. The fifth cluster, as represented by the U1420010 station (Saône River, France), exhibited two contrasting trend patterns: a positive trend from November to March, and a negative trend from April to October. Finally, the sixth cluster shows the time series for the P3234010 station (Vèzére River, France), with a dominant negative trend during June to December.

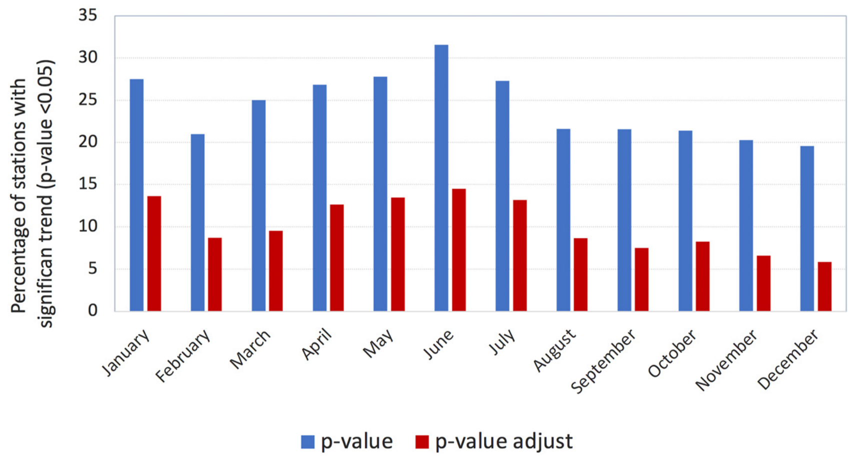

Figure 4. Percentage of stations with significant trend (p-value < 0.05) in the temporal evolution of the monthly Standardized Streamflow Index derived using the Mann Kendall test (blue) and the Mann Kendall test and false discovery rate procedure (red).

A high percentage of stations show a significant trend (adjusted p-value ($p < 0.05$)) for monthly SSI (Figure 4). Figure 5 illustrates the significance of the monthly SSI trend at the station level. In the same context, Table 1 lists the percentage of stations corresponding to each significance category. For the first cluster, which generally corresponds to Great Britain, SSI showed a positive trend from March to May, as well as in October and November. A negative trend dominated in winter (December–February) and in summer (June–September) when spatially this cluster is reduced to the north of Britain. More than 80% of the stations belonging to this cluster showed a positive trend during spring months, decreasing to a smaller percentage in October and November. In the remaining months (June–September), except for January and February, the percentage of stations with a negative trend exceeded those with a positive trend.

In the areas that correspond to cluster 2 (central regions of the continent), we identified two patterns of SSI trend: a positive trend from September to March, and a negative trend from April to August. More than 75% of the stations assigned to this cluster exhibited a negative trend from April to August, while a positive trend predominated in the remaining months (except for December). A similar bidirectional pattern was also noted for the third cluster (northern Europe), with a positive trend from October to April, and a negative trend from May to September. The highest percentage of stations (more than 60%) corresponding to this cluster showed a positive trend from October to April, meanwhile negative trends dominated in the majority of stations in the rest of the year, apart from July and August. In all months, changes in SSI over the Iberian Peninsula and southeast France (cluster 4) were negative, with >70% of stations reporting a negative trend, and in most cases, half of the gauging stations have a significant trend. Exceptionally, in December, 58% of the stations exhibited a positive trend. Two SSI patterns were noted in the regions corresponding to the fifth cluster (northern and western France and eastern Ireland): a positive trend from November to March (generally above 55% of stations), and a negative trend from April to October (>70% of stations, except for July). Finally, SSI showed a negative trend in the majority of the stations assigned to the sixth cluster in all months (south of France). In a few exceptions, the percentage of stations with positive trends were much higher in January (48%) and February (41% of stations).

3.3. Analysis of the Temporal Evolution of Hydrological Drought Events Characteristics in Europe

Figure 6 depicts changes in the duration, frequency, and severity of hydrological droughts. Results reveal that the majority (~75%) of the stations showed a non-significant trend, while only 25% of the stations exhibited a statistically significant trend. Notably, the percentages of stations with positive (increase in severity of hydrological drought) or negative (decrease in the severity of hydrological drought) trends, either significant or non-significant, were very similar. These results, a priori, suggest that there is no clear trend in hydrological drought at the continental level, indicating the importance of a regional focus.

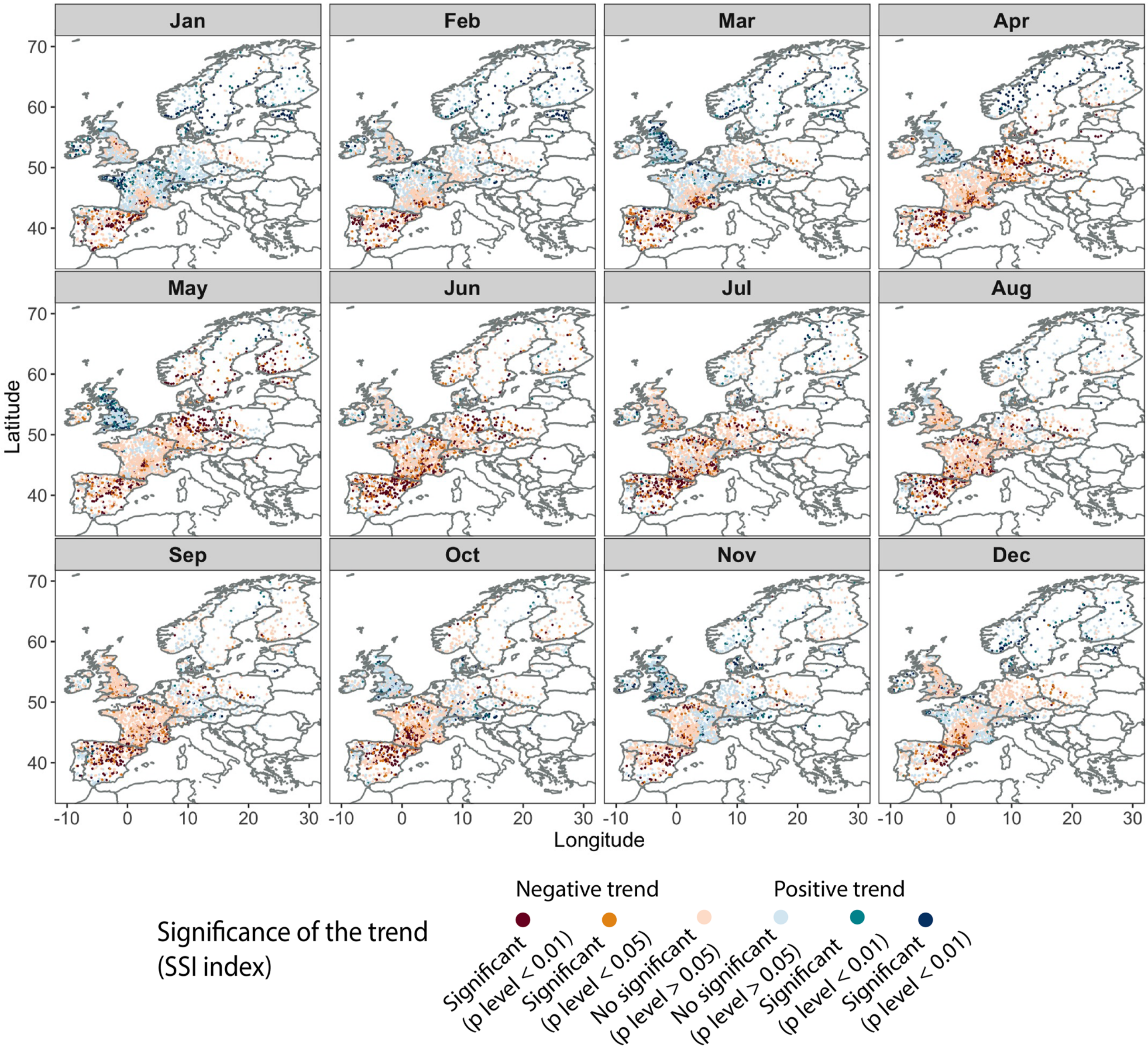

Figure 5. Spatial distribution of the direction and significance of the trends in monthly Standardized Streamflow Index over the 1962–2017 period. Each circle represents one gauging station.

There is a strong spatial relationship between the trend of the different characteristics of hydrological droughts (i.e., duration, frequency and severity) (Figure 7). Figures 8–10 illustrate the spatial distribution of the magnitude of change and the statistical significance of the trends in these characteristics. Notably, the spatial distributions of the magnitude of change and trend significance for the three different drought characteristics were very similar. In general, two dominant spatial patterns were observed, with a positive trend (i.e., toward increasing drought) in southern and central Europe and a negative trend (i.e., toward decreasing drought) in Northern Europe.

Considerable differences in the frequency, duration, and intensity of drought events were found among the different sub-regions (clusters) (Figure 11). For cluster 1 (typically corresponds to Great Britain), the negative trends of hydrological drought events predominated in most of the stations (>70%). Cluster 2 spans a wide region in central Europe (e.g., northern France, Belgium, Finland, Germany, Poland, Austria, Czech Republic and Slovakia), making trends less homogenous: non-significant positive (48% severity, 55% duration, and 72% frequency) and negative (52% severity, 45% duration, and 28% frequency) trends predominate. For cluster 3 (northern Europe),

Table 1

Percentage of Gauging Stations in Each Cluster Showing Increasing/Decreasing Trends and Their Significance Level ($p < 0.05$, $p < 0.01$, or Non-Significant) in Monthly Standardized Streamflow Index Over the Period 1962–2017

Cluster	Signal trend	Significance trend	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Number of stations		443	473	475	485	476	560	690	193	212	413	523	565
	Negative	Significative 0.01	1.35	0.21	0.00	1.24	0.63	0.54	11.30	0.00	0.00	0.24	2.10	3.54
		Significative 0.05	1.58	1.27	0.21	0.21	0.21	0.89	13.48	2.07	1.89	0.73	2.49	3.72
		No significative	37.47	34.88	5.47	14.23	6.30	46.25	52.75	54.40	68.87	15.98	21.41	60.35
	Positive	No significative	56.43	58.56	63.58	74.02	60.29	42.68	20.00	41.97	27.83	69.49	47.23	28.85
		Significative 0.05	1.58	2.96	14.95	5.57	15.13	5.18	1.88	1.04	0.47	7.99	13.58	1.59
		Significative 0.01	1.58	2.11	15.79	4.74	17.44	4.46	0.58	0.52	0.94	5.57	13.19	1.95
2	Number of stations		771	474	710	722	390	692	555	464	466	415	379	700
	Negative	Significative 0.01	0.00	1.05	0.56	18.01	46.15	18.35	9.91	6.03	3.43	1.69	1.32	1.14
		Significative 0.05	0.13	0.42	1.83	20.50	15.13	18.35	12.61	6.90	3.43	0.96	3.43	2.29
		No significative	15.18	22.36	35.63	52.91	30.26	50.14	62.52	62.28	35.41	37.11	24.27	60.00
	Positive	No significative	65.24	58.86	54.65	7.76	8.21	12.72	13.51	23.71	49.14	42.89	53.03	32.71
		Significative 0.05	10.51	10.76	4.51	0.28	0.26	0.00	0.54	0.65	4.08	7.71	9.23	2.00
		Significative 0.01	8.95	6.54	2.82	0.55	0.00	0.43	0.90	0.43	4.51	9.64	8.71	1.86
3	Number of stations		387	324	407	264	383	365	323	606	516	464	541	324
	Negative	Significative 0.01	0.00	0.00	0.00	0.00	4.96	6.30	1.55	0.50	2.33	2.37	0.37	0.00
		Significative 0.05	0.26	0.00	0.00	0.00	7.83	8.77	3.41	1.16	2.52	2.16	0.55	0.93
		No significative	6.46	5.86	5.90	13.26	45.95	44.66	32.82	29.54	48.26	34.05	19.04	7.72
	Positive	No significative	36.95	45.06	46.19	36.36	27.42	30.68	39.63	53.63	37.79	54.53	56.56	54.32
		Significative 0.05	18.60	16.67	21.62	9.09	7.83	4.93	10.22	5.94	5.04	3.66	12.20	15.12
		Significative 0.01	37.73	32.41	26.29	41.29	6.01	4.66	12.38	9.24	4.07	3.23	11.28	21.91
4	Number of stations		563	535	546	329	585	623	528	746	889	483	524	522
	Negative	Significative 0.01	21.14	25.61	26.01	19.15	15.90	35.31	42.42	25.60	22.16	19.25	16.22	12.84
		Significative 0.05	13.32	15.33	19.96	13.98	13.85	21.99	17.23	17.02	13.61	13.46	8.21	9.20
		No significative	45.12	48.22	42.31	47.11	51.97	35.15	31.25	44.50	50.51	50.72	45.99	36.21
	Positive	No significative	19.01	10.47	11.17	18.24	18.29	6.90	8.90	11.66	12.37	14.91	27.48	37.74
		Significative 0.05	1.42	0.37	0.18	1.22	0.00	0.48	0.19	0.94	0.67	0.83	1.53	2.87
		Significative 0.01	0.00	0.00	0.37	0.30	0.00	0.16	0.00	0.27	0.67	0.83	0.57	1.15
5	Number of stations		441	524	762	1034	629	542	563	307	290	793	472	515
	Negative	Significative 0.01	0.00	0.19	1.44	4.64	9.70	8.12	0.71	7.17	8.62	4.04	1.06	0.19
		Significative 0.05	0.00	0.57	2.89	7.16	10.49	11.44	1.07	13.68	12.07	5.80	2.12	0.78
		No significative	5.44	51.53	37.80	76.40	66.93	49.63	48.67	62.21	66.55	54.60	37.08	13.79
	Positive	No significative	44.22	39.31	51.05	11.41	11.76	28.23	41.92	16.29	11.72	30.90	53.39	58.83
		Significative 0.05	22.68	5.34	3.28	0.29	0.48	1.66	4.62	0.65	0.00	1.64	4.45	12.82
		Significative 0.01	27.66	3.05	3.54	0.10	0.64	0.92	3.02	0.00	1.03	3.03	1.91	13.59
6	Number of stations		619	894	324	390	761	442	565	908	851	656	785	598
	Negative	Significative 0.01	2.42	1.12	6.48	24.10	3.81	12.90	7.43	6.28	6.23	17.99	2.55	7.53
		Significative 0.05	2.75	2.80	6.17	14.36	7.23	15.61	8.50	6.28	9.99	14.18	4.84	12.21
		No significative	42.81	37.58	53.09	48.97	70.70	54.98	49.91	71.15	74.15	60.21	58.09	64.55
	Positive	No significative	46.53	47.99	29.32	12.05	17.87	16.06	32.21	14.65	8.11	7.32	30.70	15.55
		Significative 0.05	4.20	5.15	2.16	0.26	0.13	0.45	1.24	1.54	0.59	0.15	1.53	0.17
		Significative 0.01	1.29	5.37	2.78	0.26	0.26	0.00	0.71	0.11	0.94	0.15	2.29	0.00

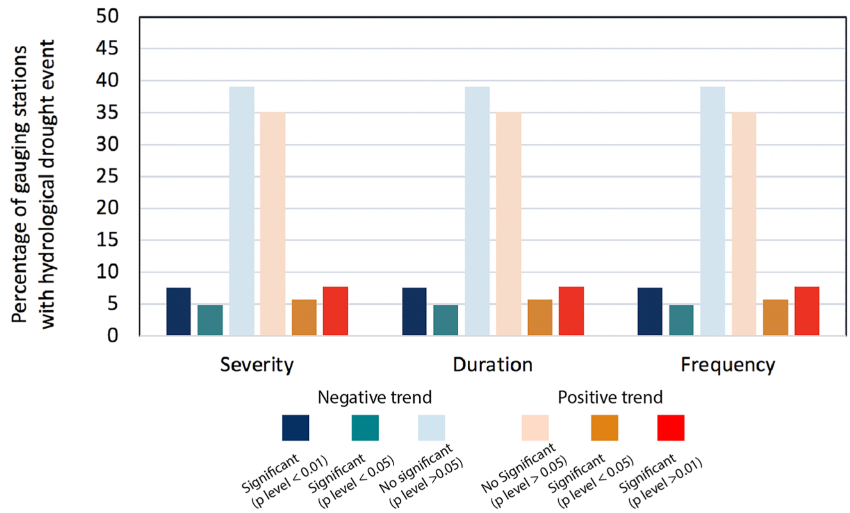

Figure 6. Percentage of gauging stations with positive/negative and significant/non-significant ($p < 0.01$, $p < 0.05$, $p > 0.05$) trends in hydrological drought event characteristics in the period 1962–2017.

the negative trends in hydrological drought events prevailed in the majority of stations (>70%). For cluster 4 (southern Europe), positive trends predominated in most stations (>80%), with a large percentage of stations showing a significant positive trend. For cluster 5 (north and west of France), a higher percentage of stations had a negative trend (71% severity, 65% duration, 58% frequency) rather than a positive trend (28% severity, 36% duration, 43% frequency). Finally, for cluster 6 (south of France), most stations (>68%) showed a positive trend.

4. Discussion

4.1. Dataset Creation

This study analyzed spatiotemporal changes in monthly streamflow and hydrological drought over Europe between 1962 and 2017, using a spatially dense data set with unprecedented geographical coverage compared to past drought studies. Previous studies have employed a much sparser network of gauging stations or focused on particular regions (e.g., Hisdal et al., 2001; Parry et al., 2012; Van Loon & Laaha, 2015). Most of the previously employed datasets (e.g., Hannaford et al., 2011; Hisdal et al., 2001; Stahl et al., 2010) depended heavily on gauging stations from central Europe, mainly Germany and northern France, and Great Britain, with less representation of regions like southern Spain, Ireland, and large portions of northern and central Europe. As compared to several available streamflow databases (e.g., Hannaford et al., 2011; Hisdal et al., 2001; Stahl et al., 2010; Vicente-Serrano et al., 2019), our newly developed data set has a greater number of stations, with

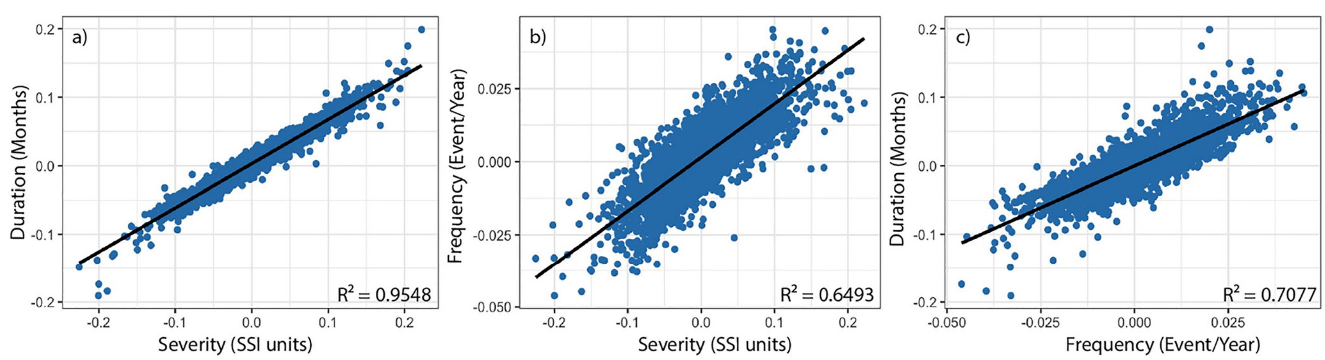

Figure 7. Relationships between (a) the severity and duration of drought events, (b) the severity and frequency of drought events, (c) the frequency and duration of drought events. The black line indicates the fitted regression line.

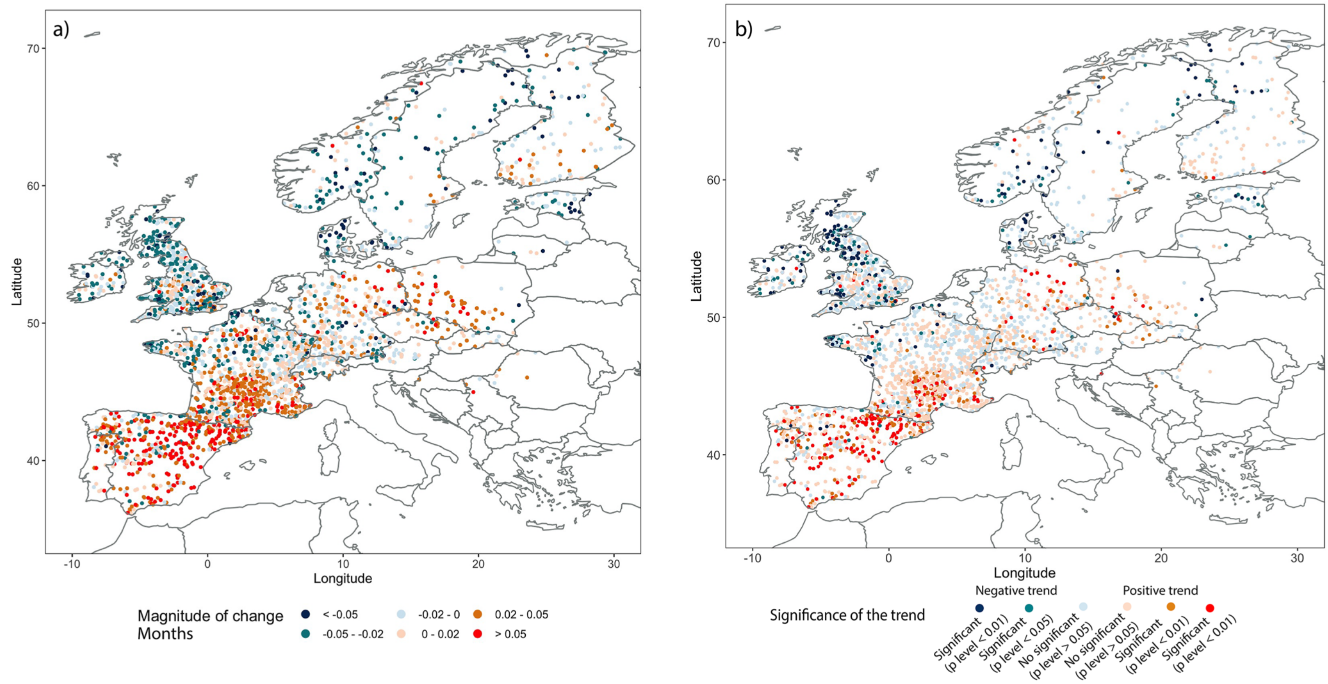

Figure 8. Trends in the duration of drought events from 1962 to 2017. (a) Spatial distribution of the magnitude of change in Standardized Streamflow Index and (b) the corresponding significance of trends (at $p < 0.05$, $p < 0.01$) over the same period. Each circle represents one gauging station.

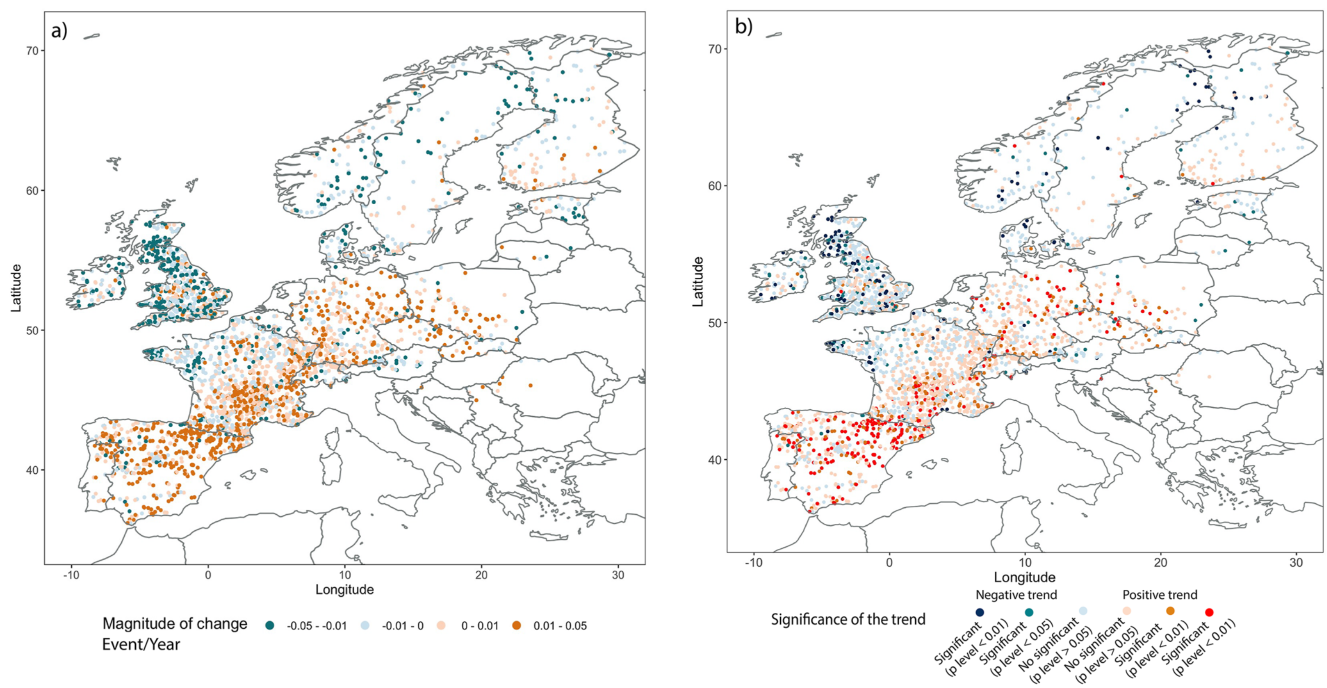

Figure 9. Trends in the frequency of drought events from 1962 to 2017. (a) Spatial distribution of the magnitude of change in Standardized Streamflow Index and (b) the corresponding significance of trends (at $p < 0.05$, $p < 0.01$) over the same period. Each circle represents one gauging station.

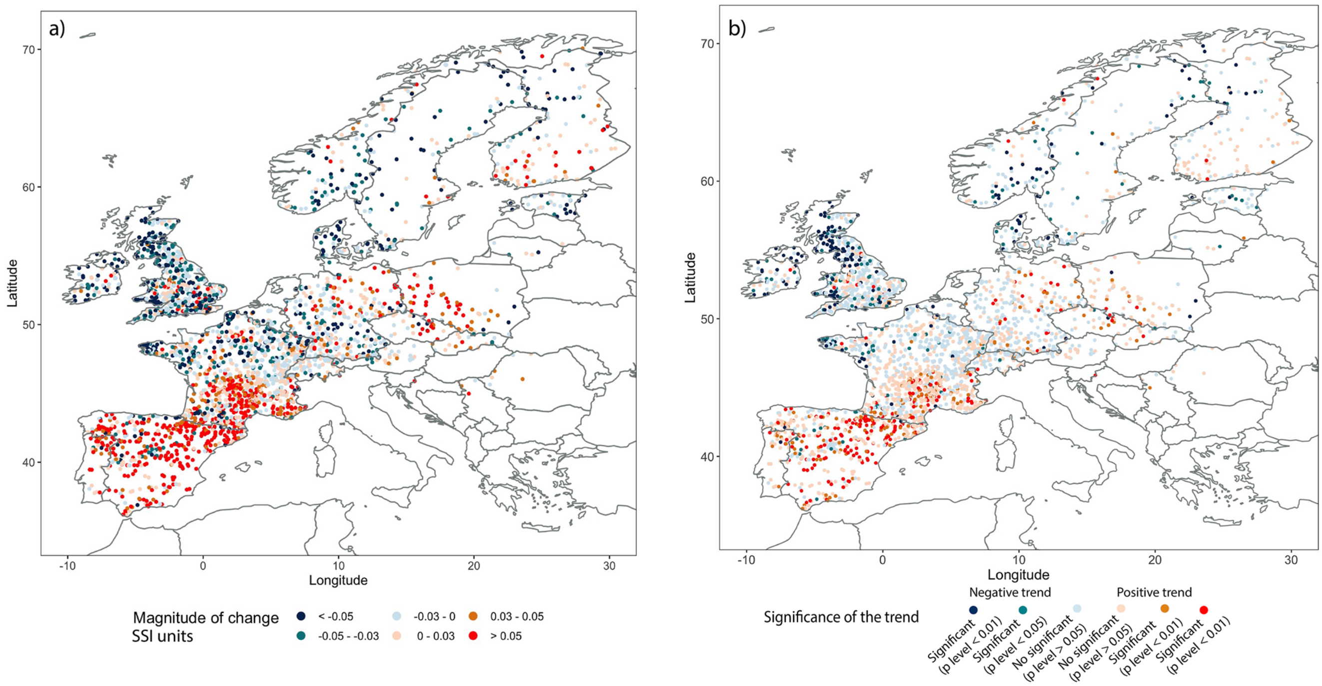

Figure 10. Trends in the severity of drought events from 1962 to 2017. (a) Spatial distribution of the magnitude of change in Standardized Streamflow Index (SSI) and (b) the corresponding significance of trends (at $p < 0.05$, $p < 0.01$) over the same period. Each circle represents one gauging station.

better representation of the different regions in Europe. This highly dense network over both space (N = 3,324) and time (1962–2017) represents a potential asset for the research community in Europe and beyond.

The spatial distribution of the study gauging stations shows spatial inequalities. There are regions of the area of study that have a large number of stations available, which are easily public access, while others present a great lack of information. Among the regions of the first case, the southwest (Portugal, Spain, France), the center-west (Switzerland and Germany), and the UK stand out. The other regions, such as Northern and central-eastern Europe and Ireland, have a homogeneous but not very dense distribution of gauging stations. It is important to highlight the lack of a good network of gauging stations with the aforementioned characteristics in the southeast and east in Europe.

4.2. Spatial Patterns of Monthly Streamflow

In our study, we identified six homogeneous regions representing the evolution of monthly streamflow in Europe over the past six decades (1962–2017). Previous studies have used this technique to establish a regionalization of streamflow characteristics in Europe. A representative example is Stahl et al. (2010) who identified 19 European regions based on a cluster analysis of historical streamflow deficiency time-series from the European Water Archive stations. Based on a cluster analysis of 579 gauges covering the period 1961–2005, Hannaford et al. (2011) defined a total of 23 homogeneous regions across Europe, stressing the complex picture of streamflow trends on a continental scale taking into account the differences that occur between the different studies due to the spatial coverage, the density of stations, the study period, the number of regions, and how droughts are defined. In addition, previous studies differ from ours in obtaining a greater number of clusters, so they focus on more complex hydrological processes of a local character. Despite this, we showed similar clustering schemes to those presented in earlier works. For example, our study defined Great Britain (cluster 1) and the Iberian Peninsula and southeast France (cluster 4) as homogeneous regions in terms of streamflow trends, which concurs with the findings of Hannaford et al. (2011) and Stahl et al. (2010).

The differences observed in each cluster between months may be expected in response to the different physical mechanisms controlling the interannual variability of climate and streamflow in the region, such as the North Atlantic Oscillation (NAO), especially during wintertime (Hannaford et al., 2013; Ionita, 2014; López-Moreno

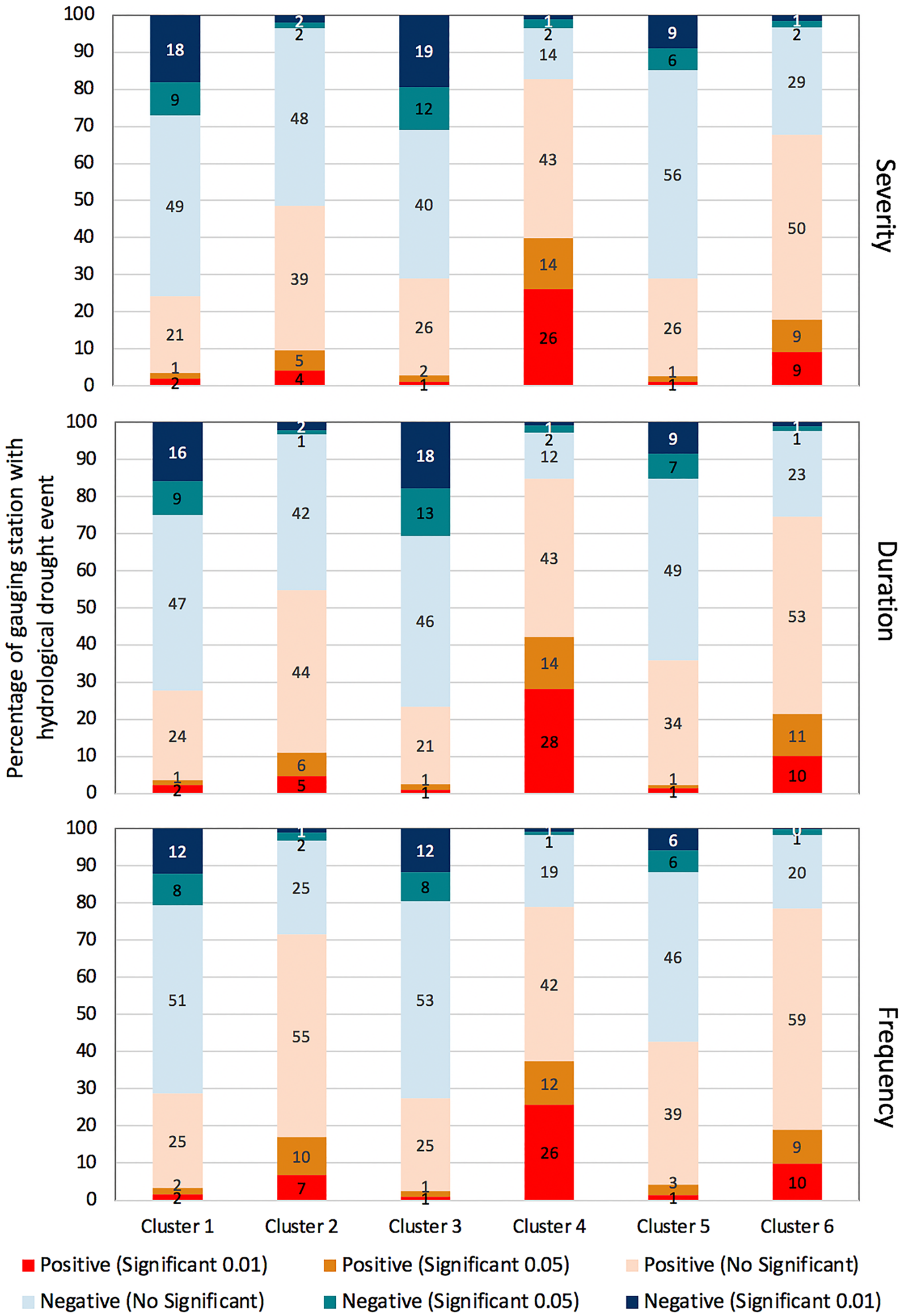

Figure 11. Percentage of gauging stations with positive/negative and significant/non-significant (at $p < 0.01$, $p < 0.05$, $p > 0.05$) trend in the severity, duration and frequency of hydrological drought events for each cluster.

et al., 2007). Numerous studies have indicated linked rainfall and stresamflow variability with the NAO in northern Europe (e.g., Bouwer et al., 2008; Wrzesinski & Paluszkiewicz, 2010) and southern Europe (e.g., López-Moreno & Vicente-Serrano, 2008; Lorenzo-Lacruz et al., 2011). Our findings suggest that climate variability, particularly the impact of winter conditions during the rest of the year, may play a role in the observed spatial patterns in drought trends (Stagge et al., 2017). These drivers may induce a delay in the response of streamflow to climate variability (Lorenzo-Lacruz et al., 2013; Steirou et al., 2017). However, other local factors may control these differences at a more detailed spatial scale, such as topography (with mountain chains acting as barriers, but also influential through storage in ice and snow at high altitudes) and lithology (notably significant storages in permeable aquifers), which have been highlighted in previous studies over both southern (Blöschl et al., 2019; López-Moreno et al., 2013) and northern Europe (Hannaford et al., 2011; Svensson et al., 2015). Other relevant factors may be related to the consumption of water by vegetation, especially during summer, or anthropogenic activities associated with dam construction and reservoir use that can affect the distribution of the flow throughout the year (Bastos et al., 2016; Guerrieri et al., 2019; Lorenzo-Lacruz et al., 2013; Mankin et al., 2019).

4.3. Monthly Streamflow Trends

Findings of this study indicate that there are no homogeneous streamflow trends in space nor over months at the continental scale (Blöschl et al., 2019). Spatially, two distinct patterns of streamflow evolution were noted. On one hand, clusters 1 (Great Britain), 3 (northern Europe), and 5 (northern and western France and eastern Ireland) all show a primarily positive trends, indicating an increase in streamflow albeit with seasonal variations (i.e., positive trends in the cold months and a slightly negative trend during warm months). These findings agree with Stahl et al. (2010) who found positive trends in the majority of catchments in western Europe during wintertime, and conversely a negative trend during warm months (April-August). In this study, cluster 2 (central), 4 (Iberian Peninsula and southeast France) and 6 (southern France) showed a negative trend, reflecting a decrease in streamflow in the majority of months. Similar spatial patterns were found at the continental (e.g., Gudmundsson et al., 2017; Stahl et al., 2010) and local scales: Spanish rivers (Ayala-Carcedo, 2001; Lorenzo-Lacruz et al., 2012), Czech rivers (Fiala, 2008), Slovakia rivers (Majercakova et al., 1997), the Boyne catchment in east Ireland (Harrigan et al., 2014), among others.

Different studies, mainly on a national scale, have been carried out to understand the causes of the streamflow trends in recent decades (Giuntoli et al., 2013; Murphy et al., 2013), suggesting different drivers as a function of the area of interest. For example, one of the possible drivers of the positive trend in monthly streamflow, especially in winter, is the slight increase in precipitation in northern Europe (Caloiero et al., 2018). In turn, an increase in the atmospheric evaporative demand was also observed (Robinson et al., 2017) in northern Europe, which may explain the decrease in streamflow during summertime. Other studies highlighted the strong influence of anthropogenic activities on the decrease of streamflow in southern Europe, including the increase in irrigated land (Pinilla, 2006), revegetation at the mountain headwaters (Beguería et al., 2003, López-Moreno et al., 2007), and the storage of water from reservoirs (Vicente-Serrano et al., 2017b). In addition to these anthropogenic activities, a strong influence of increased atmospheric evaporative demand and accordingly actual evapotranspiration was evident in southern Europe (Tomas-Burguera et al., 2021).

4.4. Changes in Hydrological Drought Severity

Most studies carried out on a continental scale have focused on the temporal evolution of streamflow, without delving into the behavior of hydrological drought events. It is important to note that major patterns in streamflow behavior do not necessarily reflect in the trends of the severity or frequency of drought events (Hisdal et al., 2001). For this reason, this work evaluated trends in the duration, frequency and severity of drought throughout Europe. Results show a strong spatial gradient that is consistent with the observed evolution of streamflow trends. Interestingly, the northern areas of Europe (e.g., Norway, Sweden, part of Finland and Germany, north and west France, Austria, Great Britain and Ireland) showed a negative trend in the different characteristics of hydrological drought, with a general decrease in the severity of droughts. Conversely, southern and central Europe (e.g., the Iberian Peninsula, south of France, parts of Germany, Poland, and Slovakia) experienced a positive trend in the different characteristics of hydrological drought events, indicating a general increase in the severity of hydrological drought. The transitional region, mainly located in France, exhibited less clear trends. These results are in agreement with previous regional assessments, even those which relied on a lower density of stations (e.g., Dalezios et al., 2000; Fleig et al., 2006; Hisdal et al., 2001; Masseroni et al., 2020; Van Lanen et al., 2013; Van Loon & Laaha, 2015).

As drought is caused by the accumulation of monthly streamflow deficits, the monthly streamflow has an impact on the frequency and severity of hydrological droughts. The trend in monthly streamflow shows that there is a north-positive and south-negative spatial pattern in winter, but this pattern is less clear in the summer. In the case of hydrological drought trends, a simple spatial pattern, north-negative and south-positive, was observed, which summarizes the impact of various drivers: trend of climatic variables mainly in northern and southern Europe, and also land cover changes and human management practices in southern Europe (Caloiero et al., 2018; Mottet et al., 2006; Teuling et al., 2019; Vicente-Serano et al., 2019). An inspection of changes in monthly streamflow reveals that the greatest agreement occurred during winter months (November-March), and on the contrary more divergence was noted during summer months. This finding indicates that hydrological drought trends are highly dependent on streamflow changes during wintertime. There are strong increases in rainfall and streamflow in the northern Europe, and this clearly results in less severe hydrological droughts; despite the slight degreases in some summer months. While recent increases in precipitation in northern Europe (Caloiero et al., 2018) may have led to a decrease in the severity of hydrological droughts in this region, the strong increase of hydrological droughts in southern Europe is much more important than what would be expected according to the climatic variables (Teuling et al., 2019). This pattern can only be explained by the strong influence of vegetation recovery in the headwaters (García-Ruiz & Lana-Renault, 2011), combined with the role of water management practices, particularly the increase in water consumption by irrigated lands (Vicente-Serrano et al., 2017a), which have doubled in surface area since the 1950s (Pinilla, 2006). All these processes may have a substantial effect on streamflow generation (Beguería et al., 2003, López-Moreno et al., 2007).

Also, anthropogenic climate change seems to have a significant impact on the observed intensification of hydrological droughts in Southern Europe (Gudmundsson et al., 2017). This effect is mainly a consequence of increased air temperature, decreased relative humidity, and the general increase in atmospheric evaporative demand (Maček et al., 2018; Tomas-Burguera, 2021). This effect can be seen in the role of the atmospheric evaporative demand in streamflow evolution in highly regulated basins, as compared to headwaters in Southern Europe (Vicente-Serrano et al., 2014). These physical mechanisms could also contribute to the declining trends of streamflow during summertime, as revealed by some regions in northern Europe. An increase of the atmospheric evaporative demand has also been identified in these regions (Robinson et al., 2017).

The present study allow determining the evolution of the hydrological drought in the last decades, which may allow more efficient drought mitigation and management measures (Bokal et al., 2014). National and regional authorities could organize irrigation methods, locations and times based on the results obtained from streamflow trend studies (Rogger et al., 2017). The authorities could promote a best management practices of water in territories affected by a positive trend in the hydrological drought (Brooks, 2013; Forzieri et al., 2014; Samaniego et al., 2019). Drought episodes frequently have a local character, so studies with a large quantity and quality of information from the gauging stations are useful for operational decision-making. In this sense, this study shows for the first time the highest density of spatial information from gauging stations for the study of hydrological drought.

5. Conclusions

Using a newly developed and dense data set of monthly streamflow gauges across Europe, this study has provided a detailed assessment of change in hydrological drought for the period 1962–2017. Results show that there are large spatial and temporal differences in streamflow across Europe, making any single statement defining changes in drought at the continental scale a challenging task. In general, it is observed that monthly streamflow as characterized by SSI showed a negative trend in southern and central European areas, while a positive trend was experienced in northern Europe. This study revealed distinct patterns at the monthly scale. In southern Europe, a negative streamflow trend was evident in all months. In central and northern Europe, and western France, a clear negative trend was observed during warm months and conversely a positive trend in cold months. Changes in streamflow were generally consistent with the large spatial patterns of hydrological drought changes, with a positive trend observed in southern and central Europe, and a negative trend predominant in northern Europe. These findings suggest that hydrological drought in Europe is not homogeneous in space and therefore is due to different drivers.

Data Availability Statement

In our study, we use the data from Agencia Catalana de l'Aigua (http://aca-web.gencat.cat/), Centro de estudios y experimentación de obras públicas, Confederación Hidrográfica del Guadalquivir (https://www.chguadalquivir.es), Environmental Protection Agency (https://www.epa.ie/), Ministère de l'Ecologie, du Développement durable et de l'Energie (http://www.hydro.eaufrance.fr/), Ministerio para la Transición Ecológica (http://ceh-flumen64.cedex.es/), National River Flow Archive (https://nrfa.ceh.ac.uk/), Sistema Nacional de Informacao de Recurso Hídricos (https://snirh.apambiente.pt/), Global Runoff Data Centre (GRDC, https://www.bafg.de/GRDC/EN/Home/homepage_node.html). In addition, we use the R platform (R Core Team, R Development Team Core, 2017: A Language and Environment for Statistical Computing). In our study new data are generated which is deposited in a repository that belongs to the public institution Pyrenean Institute of Ecology of the Higher Council for Scientific Research (Government of Spain) (http://msed.csic.es/).

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